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14. ABSTRACT

Diver visibility has been one of the key research areas in underwater vision and imaging studies. Its applications also extend into imaging system performance evaluation and prediction, which is important in MIW and ASW operations. These applications are often associated with coastal ocean waters, and this is generally translated directly into turbidity of the water column. While mostly this is the case, exceptions can lead to erroneous predictions and potentially significant consequences. We examine issues associated with such situations, both by model as well as field data, in order to reach better estimates and to explore means to compensate for such effects, to enhance diver visibility. Visibility data collected by Navy divers from clean and relatively calm waters outside Pensacola, during Sept 2001 Gorging Littoral Ocean for Warfighters (GLOW) experiments suggested a closer examination is warranted, as observed diver visibility measured at different spatial frequencies contradicts conventional model predictions. Observation data from two different days, by different divers at different depths were used. The modulation transfer of high frequency components disappears at a level much higher than those predicted by the human vision sensitivity level. Such contradictions can be resolved, once the effect of the turbulence scattering is considered using a general imaging model.

15. SUBJECT TERMS

visibility, scattering, particles, turbulence, underwater, MCM, OTF, MTF

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Diver visibility: why one can not see as far?

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ABSTRACT

Diver visibility has been one of the key research areas in underwater vision and imaging studies. Its applications also extend into imaging system performance evaluation and prediction, which is important in MIW and ASW operations. These applications are often associated with coastal ocean waters, and this is generally translated directly into turbidity of the water column. While mostly this is the case, exceptions can lead to erroneous predictions and potentially significant consequences. We examine issues associated with such situations, both by model as well as field data, in order to reach better estimates and to explore means to compensate for such effects, to enhance diver visibility. Visibility data collected by Navy divers from clean and relatively calm waters outside Pensacola, during Sept 2001 Gorging Littoral Ocean for Warfighters (GLOW) experiments suggested a closer examination is warranted, as observed diver visibility measured at different spatial frequencies contradicts conventional model predictions. Observation data from two different days, by different divers at different depths were used. The modulation transfer of high frequency components disappears at a level much higher than those predicted by the human vision sensitivity level. Such contradictions can be resolved, once the effect of the turbulence scattering is considered using a general imaging model.

Keywords: visibility, scattering, particles, turbulence, underwater, MCM, OTF, MTF

1. BACKGROUND

Diver visibility is one of the key underwater vision and imaging topics dating back to the early days of modern oceanographic research. One of the simple approaches to determine diver visibility, or turbidity of the water, has been the use of Secchi disk, for the past 150 years[1, 2]. The idea was rather intuitive, that the disappearing distance of the dinner dish would give clue to the turbidity of the water. Its deployment is simple: one lowers the traditionally white, circular disk about 30cm in diameter, from above the water into the water column, and determines the point at which it disappears from sight. The depth at which the disk can no longer be discerned against the background is defined as the Secchi disk depth. The physics behind the Secchi disk is the absorption but mostly scattering by the water and its constituents to reduce the contrast. The classical work done by Duntley relates such quantities by means of radiative transfer[2]. A recent study revealed such links from image formation, or modulation transfer perspective[1], especially in horizontal situations.

Image formation and transmission in underwater environments are always hindered by the attenuation by water and its constituents. Unlike in the atmosphere where visibility can be on the order of miles, the visual range in underwater environments is rather limited, at maximum on the order of tens of meters, even in the clearest waters. The dominant factor is typically not due to absorption, unless visible channels near the red are used. Scattering by water and particulates within the water often poses the most challenges, causing photons stray from its designated path, thus introducing the blur and loss of details within the image. This reduction of details, or high frequency components, prevents retrieval of information needed for detection and more importantly, for clear identification.

The main cause of blurry images in water is scattering, ie the photon changes path or direction. This is described by the volume scattering function (VSF) which is the probability of photons being scattered into certain directions. For ocean waters, the VSF has a strong scattering peak in very small forward angle. In more turbid waters, the peak broadens into larger angles, or higher chance for photons scatter to larger angles, which means more blur[3, 4]. This also leads to multiple scattering, where the same photon being scattered more than once before reaching detector. The resulting distribution is different from that of the single scattering, with even wider peak thus more blur.

Such effects can be best described via the point spread function (PSF) of the medium and system, or simply put, the system response to a point source, denoted as $h(x,y)$. The outcome image $g(x,y)$ is the result of the simple convolution of $h(x,y)$ and original signal $f(x,y)$, adding the noise $n(x,y)$:

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$$g(x,y) = \iint f(x_i, y_i) h(x - x_i, y - y_i) dx_i dy_i + n(x,y), \qquad (1)$$

Mathematically, it is easier to manipulate the above relationship in frequency domain, as convolutions represent simple multiplications after Fourier transforms,

$$G(u,v) = F(u,v)H(u,v) + N(u,v). \qquad (2)$$

The Fourier transformed PSF is the optical transfer function or OTF, $H(u,v)$. u, v are frequency components. When consider only the magnitude of the transform, which is adequate in underwater incoherent imaging applications, it is referred to as modulation transfer function or MTF. We know that the total OTF can be modeled in simple forms with multiplicative components as in all linear systems, while the effect of water involving mostly particulate scattering can be expressed in a closed form[1, 4, 5]

$$H_{water}(\psi, r) = e^{-D(\psi)r}, \qquad (3)$$

and

$$D(\psi) = c - \frac{b(1 - e^{-2\pi\theta_0\psi})}{2\pi\theta_0\psi}, \qquad (4)$$

where c, b are attenuation and scattering coefficients respectively. θ_0 is related to mean scattering angle. The single scattering albedo $\omega_0 = b/c$ is used to describe the amount of scattering, while the optical depth $\tau = c*r$ (r is range). The angular spatial frequency is expressed in cycles per radian.

Degradation of the image quality in a scattering medium involving turbulence has been studied mostly in atmosphere. These studies are mainly focused on modeling the optical transfer function, in an effort to restore the images obtained, such as in air reconnaissance or astronomy studies [6, 7]. Little has been done regarding the turbulence effects on imaging formation in water, mainly due to the dominant particle scattering and strong attenuation associated. This is of little surprise as anyone with experiences in coastal waters, especially those inside a harbor, or estuary areas like Mississippi, experience first-hand looks of how visibility could quickly reduce to zero in a matter of a few feet. The same applies to regions of strong re-suspensions from the bottom, both in coastal regions as well as in the deep sea. However, the effects of turbulence have been postulated to have impacts over long image transmission range [5], and supported by light scattering measurements and simulations[8]. Under extreme conditions, observations have been made that involves targets with a few feet[9]. The images obtained under such conditions are often severely degraded or blurred, on par or more than those caused by particles.

2. A DIVER VISIBILITY PARADOX

Diver visibility can be measured simply by using Secchi disk as mentioned above, or use more sophisticated targets involving different spatial frequencies, such as the USAF-type resolution charts (Fig.1). The benefits of the later is that it provides convenient spatial frequency modulation measurements, which can be used directly with underwater imaging models[1]. During Gorging Littoral Ocean for Warfighters (GLOW, Sept, 2001) experiments, measurement were made to estimate diver visibility under different range and optical conditions. Some of the data is shown in Table 1.

It can be readily seen by above visibility model (Eqs. (3) and (4)) that at the range of disappearance, the modulation transfer (H_{water}) or relative contrast can be as high as 0.24 for high frequency components (Fig.2), which is in direct contradiction of common sense and those of Blackwell's conclusions[10]. In other words, the imaging model predicts that the diver should still be able to see the high frequency group (finer line pairs), but the diver reported otherwise. The reason behind this contradiction could be the effects of turbulence as postulated above. We will apply a recently developed imaging model in the following section to solve the puzzle.

f^* / date	2mm	4mm	8mm	16mm	32mm
9/21/2001	14	28	38	44	56
9/21/2001	14	28	38	44	56
9/23/2001	20	32	40	48	54
9/23/2001	20	32	40	46	54

Table 1. Diver observed disappearing distance in feet. f^* denotes spatial frequency or line pairs, corrected for water. Each observation series were carried out by different Navy divers. No vision issues are involved.

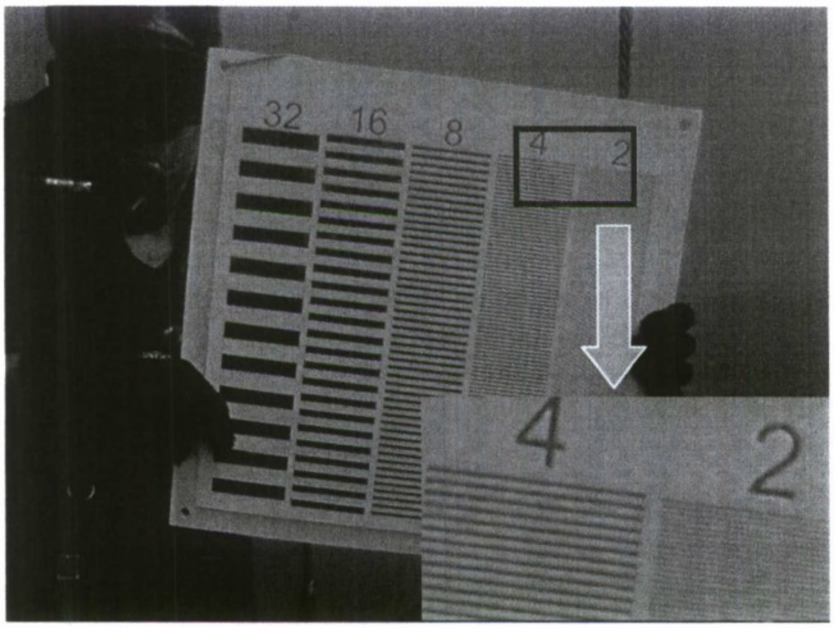

Figure 1. Sample diver visibility panel at close range. Bottom right corner shows the enlarged version of the resolution panel. Picture was taken underwater during GLOW experiment.

3. APPLYING GENERAL UNDERWATER IMAGING EQUATION

A general underwater imaging model has been developed, to include the contributions of both particle and turbulence scattering effects on imaging in the underwater environment[11]. For convenience, we will briefly outline the key results before apply the model to the current problem.

From Fourier optics, it is commonly known that spatial coherence functions between optical fields of any two points can be used to describe the irradiance distribution of the source image or object[12, 13]. The famous Young interference experiment can be seen as a special case. The modulation transfer function can be shown as equivalent to the spatial correlation function on the pupil screen. For a time-varying correlation function under wide-sense stationary conditions,

its ensemble average can be related to the spatial phase structure function when absorption variation can be neglected, such that

$$H_s(\bar{x}) = \Gamma_s(\bar{x}) = \exp(-D_\phi(\bar{x})/2) \tag{5}$$

$$D_\phi(\bar{x}) = \overline{(\phi(\bar{x}) - \phi(\bar{x} + \Delta\bar{x}))^2} \tag{6}$$

where $\phi(\bar{x})$ is the phase of the optical field on pupil plane. This is under the assumption that amplitude structure does not change over the small separation distance under examination. Other preconditions involve small perturbations of index of refraction, scale of turbulence compared large to wavelength and log-normal distribution under weak turbulence can be found in detailed discussions in listed references[13, 14].

Following the Kolmogorov model, for a fully developed turbulent flow, under the inertial regime, the power spectral density of index of refractions can be expressed in the forms of [15]

$$\Phi_n^K(\kappa, r) = K_3(r)\kappa^{-11/3} \tag{7}$$

where the superscript K denotes Kolmogorov spectrum. $K_3(r)$ is equivalent of the structure constant of the index of refraction fluctuations, which describes the intensity of the optical turbulence strength (ie index of refraction fluctuations). It is a function of kinetic energy dissipation rate and the molecular viscosity of the water. The above scalar relationship implies that the turbulence can be considered statistically isotropic, and homogenous (wide-sense stationary). Further, it is important to remember that not all turbulent flows can be described by the above spectrum[14], although experimental evidence suggests the above spectrum can be used in underwater conditions [15].

Following the approach by Fried[16], and relating the spectral power spectrum to the IOR spatial distribution[13], the OTF of optical turbulence in underwater environments can be derived as[11]

$$\begin{aligned} OTF(\psi, r) &= \exp\left[-3.44\left(\frac{\lambda}{R_0}\right)^{5/3}\psi^{5/3}\right] \\ &= \exp(-S_n \psi^{5/3} r) \end{aligned} \tag{8}$$

where

$$r_0 = 0.0239\left[\frac{4\pi^2}{k^2 K_3 r}\right]^{3/5}, \tag{9}$$

$$S_n = 1735 K_3 \lambda^{1/3}. \tag{10}$$

The key parameter that relates to turbulence structure is r_0, or Fries parameter[17], which is a function of integrated turbulent structure constant (K_3 or C_n^2 in equivalent atmospheric terms), range of propagation (r) and the optical wavelength involved. The general underwater imaging equation accounts for both particle and turbulence scattering, and takes the form:

$$
\begin{aligned}
OTF(\psi,r)_{total} &= OTF(\psi,r)_{part}\,OTF(\psi,r)_{turbu} \\
&= \exp\left[-ar+br\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}-1\right)\right]*\exp\left(-S_n\psi^{5/3}r\right) \\
&= \exp\left[-ar-br\left(1-\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)-S_n\psi^{5/3}r\right]
\end{aligned}
\tag{11}
$$

It is easy to see that OTF(0,r)=exp(-ar). It is also worth mentioning that in practice, the OTF is often normalized by its DC component. This can be important in situations especially when automatic gain control is applied.

Assuming that the turbulence structures during GLOW is isotropic and homogenous, and in fully developed inertial stage, a characteristic seeing parameter for underwater imaging can be introduced (R_0), which is equivalent of Fried parameter at 1m distance in water[11]. If one can assume that the discrepancies between observation and model is solely that of the effects by turbulence, such effects can be estimated by taking away the effects of particle scattering from the tota Blackwell criterion (ie 2%). This sets R_0=0.004.

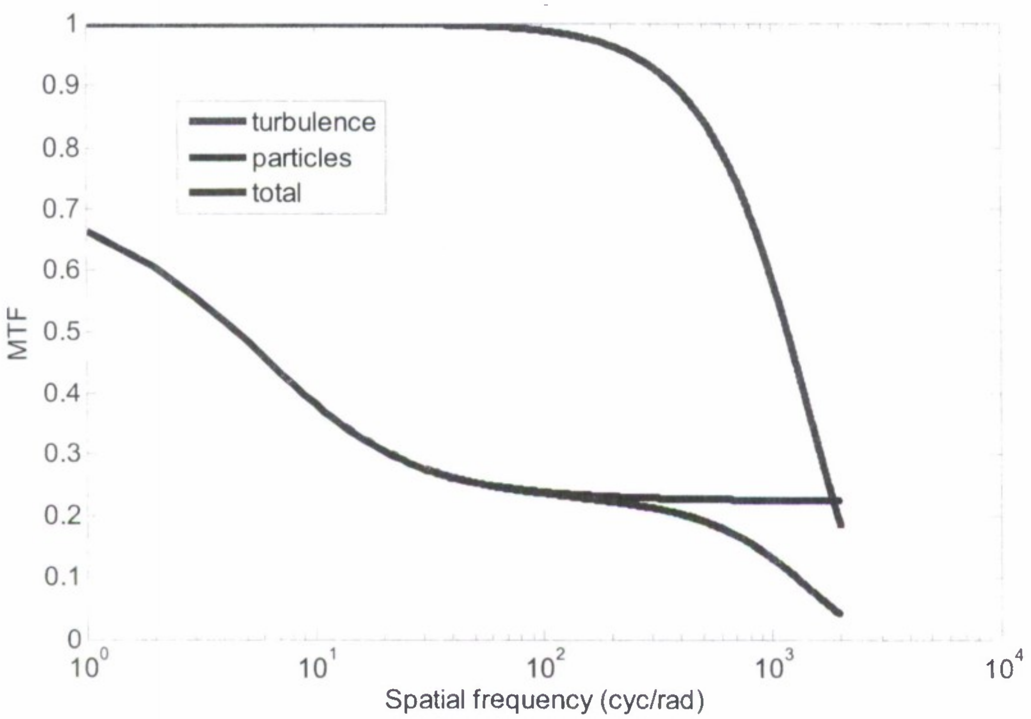

Figure 2. Effects of turbulence and particle scattering on OTF. Top to bottom: turbulence scattering, particle scattering, and the combined (multiplicative) effects.

The effects of turbulence on underwater imaging has been discussed and demonstrated previously[9], albeit qualitatively. It has long been postulated that such effects will only pose significant challenge once high resolution imaging becomes an issue, or in extreme turbulent environments[3]. Using results above (Eq.11), we can model what happened during GLOW experiment using sample values from Sept 21, 2001 field measurements. The range is set at 5m. The water has a total attenuation coefficient of 0.3m^{-1}. If only particle scattering were present, the modulation

transfer of high frequency components disappears at a level following that of Eq. (4), and shown by the middle (green color) curve in Figure 2. This value (0.24) is much higher than those predicted by the human vision sensitivity level[10]. Such contradictions can be resolved, once the effect of the turbulence scattering is considered (blue or top curve), and properly included (red or bottom curve).

Figure 3 includes all observations shown in Table 1, using particle-scattering only data from Sept 23 for clarity. One can see that with only one exception of Sept 21 observation, all relative contrast values are around 0.02, in line with Blackwell criterion. Contrasting to the total contribution of both particle and turbulence scattering, the particle-only results clearly show high contrast values at high spatial frequencies.

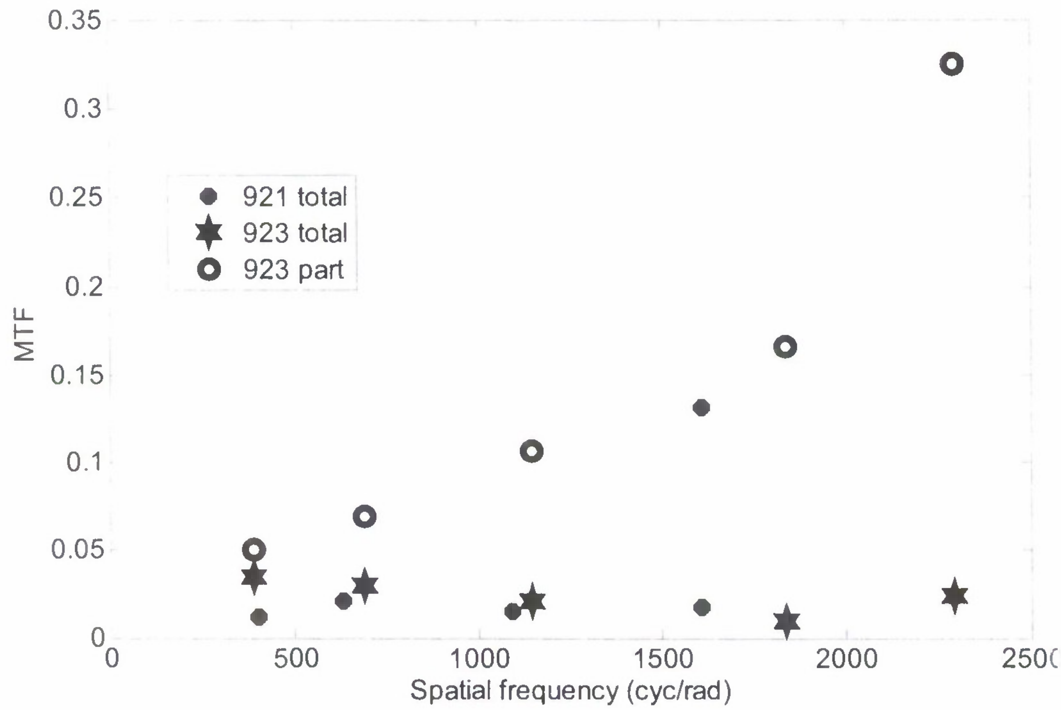

Figure 3. Combined effects of particle and turbulence scattering in terms of contrast threshold from diver observations from two different days (see text for details).

3. CONCLUSION

This paper discusses the effects of turbulence on imaging outcome in natural environments. Specifically, we demonstrate that the previous diver visibility model based only on particle scattering can lead to erroneous predictions under certain conditions. When the accumulative effects of turbulence scattering is included, by using the general underwater imaging equation which is based on Kolmogorov power spectrum, we are able to explain the observed discrepancy, assuming weak path radiance contribution. Further validation of the theory is necessary, especially under different turbulence conditions and particulate concentration. The application range of the developed theory should also be tested, along with different turbulence models and subregimes.

4. ACKNOWLEDGEMENTS

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